METHOD AND SYSTEM FOR EQUALIZING COMMUNICATION SIGNALS

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of priority to U.S. Provisional Patent Application Serial Number 60/457,655, entitled "Method and Mechanism for Improved Equalization Control Loop," and filed March 26, 2003. The subject matter of U.S. Provisional Patent Application Serial Number 60/457,655 is hereby incorporated by reference.

FIELD OF THE INVENTION

The present invention relates to the field of communications, and more specifically to signal processing circuitry associated with a receiver that provides adaptive equalization of a communications signal.

BACKGROUND

Typical transmission media for digital communication systems are both lossy and dispersive. These imperfections frequently result in impairments such as attenuation and inter-symbol interference (ISI) in signals that propagate through such media. These impairments increase in severity in correlation to increasing signal frequency and increasing channel length. In a typical digital communication system, an input signal, which is often a series of pulses sequences, is transmitted by a transmitter across a transmission medium and is

corrupted by noise. The received signal is input to a receiver, which processes the signal to generate an output signal. The receiver may include an equalizer, which may be fixed or adaptive. The equalizer compensates for the signal distortions induced by the transmission medium, restoring the fidelity of the received signal to a degree comparable to that of the transmitted signal. In many applications, a receiver needs to accommodate a variety of data transmission rates, signal spectra, and channel lengths, all of which can affect the amount of distortion that the received signal exhibits. Hence, an adaptive equalizer typically offers benefits over a fixed equalizer since the amount of compensation required to adequately restore signal fidelity may not be known a priori.

A variety of conventional adaptive equalizer architectures are known in the art. A specific architecture is sometimes selected for an application based on the channel characteristics of that application and the correlation between those channel characteristics and the various parameters associated with the architecture. Bode equalizers, as described in U.S. Patent 2,096,027, are a common type of adaptive equalizer that are suited to applications in which the channels can be simply parameterized. In particular, conventional Bode equalizers typically address channels where the signal distortion versus frequency can be represented with a known prototype function scaled by a single parameter corresponding to channel length. However, conventional Bode equalizers often provide insufficient performance in applications with channels that do not meet these criteria.

Various conventional techniques for equalizing signals exist in the art. One technique involves controlling an adaptive equalizer based on a comparison between the signal energy in a first frequency band and the signal energy in a second frequency band. The two frequency bands are chosen so that the respective signal energies in each band are nominally equivalent for an ideal signal spectrum. The adaptive equalizer applies an amount of compensation to the received signal according to a control variable. A control circuit adjusts the control variable of the adaptive equalizer based on the difference in signal energies between the two bands. When the measured signal energies are equivalent, the equalizer is adequately compensating for the channel distortions on the received signal, and the control variable settles on a stable value. The adaptive control circuit continues to monitor the two frequency bands of the equalized signal so that the equalizing filter can be adapted for any subsequent channel variations that may change the amount of distortion applied to the transmitted signal.

A conventional circuit **100** based on this conventional adaptive control technique is illustrated in Figure 1. The equalized signal **102** is tapped off before it is input to the comparator **103** and split into two parallel control signals **161** and **162**, which are coupled to a control circuit **110**. The first control signal **161** is input to a first band-pass filter **163**, whose pass band correlates to the first frequency band of interest. The output of the first band-pass filter **163** is fed to a first power detector **164**, which provides a measure of the signal energy contained within the pass band of the first band-pass filter **163**. The second control signal

162 is input to a second band-pass filter **165**, whose pass band correlates to a second frequency band of interest that is higher in frequency than the first. The output of the second band-pass filter **165** is fed to a second power detector **166**, which provides a measure of the signal energy contained within the pass band of the second band-pass filter **165**. For a 270 Mb/s non-return-to-zero (NRZ) data stream, a typical first band-pass filter **163** would have a pass band from 10 MHz to 30 MHz, and a typical second band-pass filter **165** would have a pass band from 50 MHz to 70 MHz.

In practice, the power detectors **164**, **166** may be realized as simple squaring blocks, with a low-pass integrating filter (not shown in this figure) included in each power detector **164**, **166** so that the outputs of the power detectors **164**, **166** are slowly varying compared to the data rate of the quantized signal **104**. Typically, the bandwidth of these integrating filters will be several orders of magnitude less than the data rate. The outputs of the power detectors **164**, **166** correspond to an analog estimate of the statistical variances (i.e. the square of the standard deviation) of the respective control signals **161**, **162**. Alternatively, full-wave rectifiers or half-wave rectifiers (not shown) may be used in place of a squaring block within the power detectors **164**, **166**. With the rectifier implementation, the outputs of the power detectors **164**, **166** no longer correspond to error variances. Instead, the power detector outputs represent the approximate 1-norm of the respective control signals **161**, **162**, which still correlates to signal energy in the desired frequency range. Those skilled in the art appreciate that determining the "1-norm" of the respective control signals **161**,

162 typically comprises integrating the absolute values of the control signals **161**, **162**.

The outputs of the two power detectors **164**, **166** are input to a summation node **167** where the second integrated control signal is subtracted from the first integrated control signal to generate an error signal **168**. A control block **169**, which may be as simple as a scaling amplifier and an added offset, converts the error signal **168** into the control variable **106**. The error signal **168** correlates to the amount of compensation applied by the equalizing filter **101**. If the error signal **168** is positive, the equalizing filter **101** is under-compensating for the channel distortion, and the control block **169** increases the level of equalization by increasing the control variable **106**. If the error signal **168** is negative, the equalizing filter **101** is over-compensating, and control block **169** decreases the level of equalization by decreasing the control variable **106**. If the error signal **168** goes to zero, the equalizing filter **101** reaches it optimal state, and the level of equalization remains fixed as long as the error signal **168** remains zero.

In an alternative scenario, the signal energies in the frequency bands specified by the band-pass filters **163**, **165** need not be equal, but merely fixed in relation to each other for an ideal, non-distorted signal. In such a case, the frequency-dependent distortions imposed on the signal by the channel causes the difference in the signal energies to differ from the known, fixed amount of the ideal case. The control circuit can be made to account for this fixed difference by adding fixed gain blocks (not shown in Figure 1) to the outputs of the power detectors **164**, **166** so that the outputs are scaled to account for the known offset of

the ideal signal. Hence, when the signal energies as measured by the power detectors **164, 166** differ by the known, fixed amount, the gain block will offset the difference and the error signal **168** will still go to zero. That is, when the equalized signal exhibits signal energies in the first and second frequency bands that differ by the fixed amount of the ideal case, the control circuit **110** will fix the level of equalization.

The adaptive control system of Circuit **100**, as illustrated in Figure 1, provides a degree of immunity to variations in the amplitude of the transmitted signal **105** since any changes in transmit amplitudes manifest themselves in both the first and second control signals **161** and **162**. However, this circuit **100** has a significant disadvantage in that its performance is based on the assumption that the signal energies in the frequency bands specified by the band-pass filters **163, 165** should be fixed in relation to each other when the equalizer reaches its optimal state.

This assumption is based on a condition of having an ideal signal spectrum, which is theoretical and not indicative of typical real-world circumstances. This assumption further constrains the applicability of the control method to a specific and narrow range of data rate and a specific signal spectrum. Changes in data rate or the type of signaling used at the transmitter can cause the equalizer control variable to settle at a non-optimal value since the transmitted signal may violate the underlying assumption that the signal energy in the two pass bands is equal, or at least different by a known and fixed amount.

For example, the exemplary pass bands given above would typically be ill-suited for data rates other than 270 Mb/s or for certain types of encoding, such as 8-bit/10-bit (8b/10b), which can dramatically change the transmitted signal spectrum. In other words, the equalizing filter **101** is adjusted based on prior knowledge of a specific ideal signal spectrum and an observation as to how much the equalized signal spectrum differs from the ideal. Consequently, one limitation of the conventional art, as illustrated in Figure 1, is that the circuit's utility is somewhat limited to an undesirably narrow range of data rates and signal spectra.

Another conventional approach to providing equalization to a communication signal is based on controlling equalization on the basis of monitoring the edge energy of an equalized signal, as illustrated in Circuit **200** of Figure 2. The equalized signal **102** is tapped off before it is input to the comparator **103** and fed to a first high-pass filter **251**. The cutoff frequency of the high-pass filter **251** is typically chosen to be at least half of the lowest data rate that the equalizer circuit **200** should accommodate. The output of the first high-pass filter **251** is input to a first power detector **252**, which provides a measure of the edge energy of the equalized signal **102**. The quantized signal **104**, which will have fast rise and fall times due to the limiting amplifier contained with the comparator **103**, is tapped off and fed to a second high-pass filter **253**. The output of the second high-pass filter **253** is input to a second power detector **254**, which provides a measure of the edge energy of the quantized signal **104**. The second high-pass filter **253** and the second power detector **254** are typically similar to the first high-pass filter **251** and the first power detector **252**, respectively. The power

detectors **252**, **254** in Circuit **200** may include an integrator and are typically similar to those used in Circuit **100**, which is illustrated in Figure 1 and discussed above.

The outputs of the two power detectors **252**, **254** in Circuit **200** are input to a summation node **255** where the output of the first power detector **252** is subtracted from the output of the second power detector **254** to generate an error signal **256**. A control block **257**, which may be a simple scaling amplifier and an added offset, converts the error signal **256** into the control variable **106**. The error signal **256** correlates to the amount of compensation applied by the equalizing filter **101**. If the error signal **256** is positive, the quantized signal **104** has more edge energy than the equalized signal **102**, indicating that the equalizing filter **101** is under-compensating for the channel distortion. Subsequently, the control variable **106**, and thus the level of equalization, will increase. If the error signal **256** is negative, the quantized signal **104** has less edge energy than the equalized signal **102**, indicating that the equalizing filter **101** is over-compensating. Subsequently, the control variable **106**, and thus the level of equalization, will decrease. If the error signal **256** goes to zero, the edge energies of the equalized and quantized signals **102**, **104** are equivalent, indicating that the equalizing filter **101** has reached a state of optimal compensation. Subsequently, the level of equalization will remain fixed as long as the error signal **256** remains zero.

One advantage of the conventional adaptive control circuit **200** illustrated in Figure 2 over the conventional circuit **100** illustrated in Figure 1 and some other conventional circuits is that it is applicable to a somewhat broader range of data

rates and signal spectra. This circuit **200** is applicable to a broader range of signal spectra and data rates because the equalized signal **102** is compared to the quantized signal **104**, which will have a similar spectrum to the equalized signal **102** once the equalizer control variable has been optimized. In effect, the quantized signal **104** provides an improved exemplary signal to the control loop **210** to which the equalized signal **102** can be compared for the purpose of adapting the equalizing filter **101** with reduced dependence on data rate, signal encoding, or modulation technique.

However, the architecture of Circuit **200** is based on the assumption that the equalized and quantized signals **102**, **104** have similar peak-to-peak amplitudes. Since this assumption can be imperfect in some applications, this circuit **200** may exhibit a disadvantageous sensitivity to changes in the transmit amplitude. Changes in transmit amplitude can change the transmitted signal spectrum by either increasing or decreasing signal energy. This change in the magnitude of the power spectral density (PSD) is manifested in the equalized signal **102** as well, but not in the quantized signal **104** since its amplitude is fixed by the limiting amplifier in the comparator **103**. This discrepancy is not fully accounted for by the control loop **210** of the circuit **200** and can skew the adaptation of the control variable **106** to a suboptimal value.

A conventional approach to partially alleviating this problem is to add an automatic gain control (AGC) amplifier (not shown) to the circuit **200** immediately following the equalizing filter **101** but before the control signals are tapped off. This is not an ideal solution for a number of reasons. First, since the

AGC setting is determined by a control variable based on an error signal, the equalizer control variable may not adapt properly since the two parameters (the equalizer control variable and the AGC control variable) simultaneously adjust based on a single observable (the error signal). In some instances, a fixed equalizer may be used with the control variable adjusting the AGC instead, but this usually provides only an overall gain control to the equalized signal and may not sufficiently compensate for the channel loss and dispersion over all relevant frequencies. While having an AGC in the data path of the receiver helps account for variations in transmit amplitude, it impedes the ability of the control loop to accurately adjust the equalizer control variable, since a control variable will be required to additionally control the AGC. In other words, connecting an AGC and an equalizer in a series arrangement can cause operational interference between these devices. Furthermore, in this architecture, AGCs can be undesirable for high-speed receivers since the bandwidth limitation of the AGC itself has a propensity to degrade the equalized signal.

To address these representative deficiencies in the conventional receiver art, what is needed is a capability for equalizing signals that accommodates a wide variance in operating conditions that are not necessarily known a priori. Furthermore, an equalizing circuit is needed that equalizes signals that have suffered various types and levels of signal degradation from transmission through lossy and/or dispersive transmission media. Such a capability would facilitate providing cost effective communications in diverse applications.

SUMMARY OF THE INVENTION

The present invention supports processing communication signals to correct for signal distortion, such as signal distortion caused by transmission over a cable, backplane, or other medium. The present invention further supports correcting for such signal distortion over a broad range of communication data rates and operating conditions.

In one aspect of the present invention, a receiver circuit can correct signal distortion in a communication signal with an adjustable filter or an adjustable system of filters. The receiver circuit can include a component, such as a comparator, coupled to the adjustable filter. The comparator can compare the filtered communication signal to a reference signal and can amplify the result of the comparison. The receiver circuit can also include a control circuit that can adjust the adjustable filter based on a measurement of a characteristic of the communication signal leading into the comparator and another measurement of the characteristic of the communication signal leading out of the comparator. The control circuit's adjustments to the adjustable filter can equalize the communication signal, in effect minimizing the difference between the characteristic of the communication signal leading into the comparator and the characteristic of the communication signal leading out of the comparator while taking into account variations in the amplitude of the communication signal.

Taking into account variations in the amplitude of the communication signal can include monitoring slow variations, such as variations occurring on a per-second time scale, in the signal strength leading into and out of the

comparator. In other words, the control circuit can adjust the adjustable filter. In response to the control input, the adjustable filter can cause a measured characteristic of the communication signal to be essentially equivalent on both the input and the output side of the comparator. Additionally, the control circuit can compensate for amplitude-related variations in the raw measurement of the characteristic by scaling the characteristic on each side of the comparator according to the amplitude on the opposite side.

In another aspect of the present invention, the communication signal can include high-frequency signal components and low-frequency signal components. High frequency components of a communication signal can be signal components that have a frequency higher than half the data rate of the signal. Low frequency components of a communication signal can be signal components that have a frequency lower than half the data rate of the signal. The characteristic of the communication signal that is equalized on both sides of the comparator can be an intensity or energy level in the high-frequency signal components. Taking into account variation in the amplitude of the communication signal can include monitoring the intensity or energy level in the low frequency components.

The discussion of processing communications signals presented in this summary is for illustrative purposes only. Various aspects of the present invention may be more clearly understood and appreciated from a review of the following detailed description of the disclosed embodiments and by reference to the drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates a functional block diagram of a conventional adaptive equalizer control loop.

Fig. 2 illustrates a functional block diagram of a conventional adaptive equalizer control loop.

Fig. 3 illustrates a functional block diagram of a communication system according to an exemplary embodiment of the present invention.

Fig. 4 illustrates a functional block diagram of a receiver circuit according to an exemplary embodiment of the present invention.

Fig. 5 is a graph illustrating the magnitude of the frequency response for an exemplary channel comprising 300 meters of coaxial cable according to an exemplary embodiment of the present invention.

Fig. 6A is a graph illustrating an exemplary pulse sequence before transmission across a lossy, dispersive channel according to an exemplary embodiment of the present invention.

Fig 6B is a graph illustrating an exemplary pulse sequence after transmission across a lossy, dispersive channel according to an exemplary embodiment of the present invention.

Fig. 7 is a graph illustrating a power spectral density of an exemplary pulse sequence before and after transmission across a lossy, dispersive channel according to an exemplary embodiment of the present invention.

Fig. 8 is a graph illustrating a power spectral density of an exemplary pulse sequence with varying edge energies according to an exemplary embodiment of the present invention.

Fig. 9 illustrates a functional block diagram of an adaptive Bode equalizer according to an exemplary embodiment of the present invention.

Fig. 10 illustrates a functional block diagram of an adaptive equalizer control loop according to an exemplary embodiment of the present invention.

Fig. 11 illustrates a functional block diagram of an adaptive equalizer control loop according to an exemplary embodiment of the present invention.

Fig. 12 illustrates a process for adaptive equalization according to an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

The present invention supports controlling an adaptive equalizer, such as a Bode equalizer or another type of equalizing filter, to provide compensation for frequency-dependent loss and ISI induced by a transmission medium while accounting for variations in the transmit amplitude and signal spectrum of a communication signal. Hence, the present invention can accurately adjust an equalizer to provide optimal or adequate compensation to the communication signal while accommodating significant variations in transmit amplitude, data rate, scrambling techniques, modulation methods, and other system variations.

The transfer function of an exemplary channel, having *m* zeros and *n* poles, may be represented by the following equation:

$$H(s) = \frac{(s+z_1)(s+z_2)\cdots(s+z_m)}{(s+p_1)(s+p_2)\cdots(s+p_n)}.$$

Ideally, an equalizing filter will have a transfer function that is exactly the inverse of the channel transfer function. That is, the zeros of the filter transfer function will exactly cancel the poles of the channel transfer function, and the poles of the filter transfer function will exactly cancel the zeros of the channel transfer function. Since the frequency response of a channel may vary due to numerous factors, such as length or temperature, many applications require that an equalizing filter be capable of correcting distortions for a range of channel variations.

An adaptive or adjustable equalizing filter can, in response to a signal or signals from a control circuit, provide an adjustable level, or degree, of signal conditioning, filtering, or equalization. That is, the control signal or signals adjust the locations of the zeros (and in some cases, the poles as well) of the filter transfer function to best approximate the inverse transfer function of a specific channel. Furthermore, the amount of equalization applied by the filter to a communication signal can vary with frequency. For example, an adaptive or adjustable equalizing filter might receive a signal with frequency components spanning from 100 to 600 megahertz (MHz). This filter might apply a gain of 100 to the signal components between 400 MHz and 600 MHz while applying a gain of 10 to the signal components between 100 MHz and 400 MHz.

Figure 3 illustrates a functional block diagram of a communication system **300** according to an exemplary embodiment of the present invention. An input

communication signal **301** feeds a transmitter **302**, which sends it through a transmission medium **303**, such as a cable or backplane, to a receiver **306**. As the signal **301** propagates through the transmission medium **303**, it is contaminated by noise **304** so that the signal **105** delivered to the receiver **306** is distorted, attenuated, and/or otherwise impaired with respect to the original input signal **301**. The receiver **306** converts the impaired signal **105** to a form, such as a digital, quantized signal, from which encoded information can be readily accessed.

Figure 4 illustrates an exemplary adaptive equalizer circuit **400** that can be included in the receiver **306** to restore signal fidelity to the received signal **105** according to an exemplary embodiment of the present invention. The received signal **105** is input to an adaptive equalizing filter **101**. The output **102** of the equalizing filter **101**, which will be referred to as the equalized signal **102**, is then input to a direct current (DC) restoring comparator **103**. The comparator **103**, which includes a limiting amplifier, restores the DC component of the original signal **301** to the quantized signal **104** via quantized feedback or a similar technique. The quantized signal **104** then closely replicates the original signal **301** since the limiting amplifier digitizes the equalized signal **102**, reshaping the pulse train with fast rise and fall times. An adaptive control circuit **410** uses the output of the equalizing filter to generate a control variable **106** (designated as alpha "α" in the discussion below) that, when fed-back to the equalizing filter **101**, adjusts the amount of compensation applied to the received signal **105**. The quantized signal **104** can also be used by the adaptive control mechanism to generate the control variable (illustrated in Figure 2 with the dashed data path **407**).

Cable loss, L_C, though the transmission medium **303** can often be approximated in the frequency domain as

$$L_C(f,l) = e^{-Al(1+j)\sqrt{f} - jBlf - Clf},$$

where f is frequency, l is the length of the cable, and A, B, and C are derived from the skin depth and dielectric constant of the cable. The magnitude of the frequency response for an exemplary coaxial cable that is 300 meters long is illustrated in the plot **500** of Figure 5. Cable losses increase in correspondence to increased frequency of a signal propagating in the cable. For example, propagation over the 300-meter cable attenuates a 1200-MHz signal by approximately 100 dB so that about one percent of the signal launched into one end of the cable is emitted from the opposite end. A typical communication signal has numerous frequency components rather than one pure frequency. Propagation over the cable causes a different level of attenuation for each of these signal components. Consequently, the aggregate communication signal exhibits distortion that is not readily correctable with a single application of gain. The present invention can apply a frequency-dependent level of gain to a communication signal to overcome frequency-dependent loss.

Neglecting reflection effects (an acceptable assumption for many backplanes) the loss of a backplane trace can be approximated using similar functional dependencies as cable loss, although an extra term with an f^2 dependence can be included in the exponent. As the frequency dependence of the channel characteristics becomes increasingly complex, more sophisticated

adaptive equalizer architectures can be used to adequately restore signal fidelity. A backplane trace subjected to significant sources of reflection in the data path and/or crosstalk interference from neighboring channels is an example of such a complex channel.

To better understand the signal distortions requiring compensation by an equalizer, Figures 6A and 6B show an exemplary pulse sequence **600** of a near-ideal 270 Mb/s NRZ signal before and after transmission across the exemplary, 300-meter cable plotted in Figure 5. The launched signal **600** in Figure 6A has a peak-to-peak voltage of 800 millivolts (mV) and a 10%-90% rise time of 0.64 nanoseconds (ns). The received pulse sequence **650** in Figure 6B clearly illustrates the attenuation and dispersion imposed on a signal by a channel. Frequency-dependent losses impart greater attenuation on the higher frequency signal components than on the low frequency components. The high-frequency components are associated with the edges, or vertical transitions, of the launch signal **600**, as depicted in Figure 6A. In contrast, the received signal **650** in Figure 6B is dominated by low frequency signal components that appear as an oscillation without steep edges. That is, transmission over the exemplary cable attenuates high-frequency signal components of a communication signal **600**, removes sharp edges in a pulse sequence **600**, and creates a distorted signal **650**. The present invention can correct such a distorted signal **650** so that it is properly conditioned for extracting information coded thereon.

PSD plots for the launched signal **751** and the received signal **752** are shown in Figure 7. The graph **700** of Figure 7 illustrates the power of the

communication signals **600**, **650** distributed in frequency and thus facilitates observing the general shape of a signal's spectrum. Below 100 MHz, the PSD difference between the launched signal spectrum **751** and the received signal spectrum **752** is less than approximately 30 dBm/Hz (decibels as referenced to one milliwatt per Hertz). Above 400 MHz, this difference is greater than approximately 55 dBm/Hz. In other words, the low-frequency components of the communication signals **600**, **650**, which are on the left side of the graph **700** exhibit less loss as a result of transmission over the exemplary cable than do the high-frequency components on the right side of the graph **700**.

The adaptive equalizer of the present invention can monitor the spectrum of the equalized signal **102** (or a related parameter such as edge energy) and adjust the level of compensation provided by the equalizer **101** based on how much that spectrum (or the related parameter) differs from the near-ideal case **751**. That is, the present invention can include circuitry that amplifies high-frequency components of a communication signal more than low-frequency components of a signal. Such frequency-selective amplification can boost the received signal **650** so that it exhibits a PSD plot that is similar to the PSD plot **751** of the launched signal **600**.

The relationship between edge energy and signal spectrum is illustrated in Figure 8, which provides a plot of the PSD for a 270 Mb/s NRZ signal **851** with a 0.64 ns rise time and a plot of a similar signal **852** with a 2.68 ns rise time. Below 100 MHz, the spectra of both signals **851**, **852** are nearly identical, yet because the signals have different edge energies due to the discrepancy in rise times, the high-

frequency portion of the spectra **851**, **852** are significantly different. Hence, comparing the edge energies of two different signals with the same data rate gives an approximate measure of the differences between the two signal spectra.

Rise time is typically associated with signal quality so that fast rise time usually indicates better signal performance than slow rise time. Consequently signal **851**, which has a rise time of 0.64 ns, is a more desirable signal than signal **852**, which has a rise time of 2.68 ns. Below approximately 250 MHz, the two signals **851**, **852** exhibit comparable levels of energy. Above 250 MHz, the 0.64-ns-rise-time signal **851** has higher energy than the 2.68-ns-rise-time signal **852**. Such signal quality is, therefore, visible in the spectrum **851** by the greater signal energy carried in the upper frequency range. By restoring the high-frequency energy content of a received communication signal to a robust level, the present invention can correct degraded rise time so that information can be readily extracted from the signal.

Turning now to Figure 9, the present invention can provide an improved technique for adaptation of a Bode equalizer. An exemplary adaptive Bode equalizing filter **101** is illustrated in Figure 9 according to an embodiment of the present invention. The received signal **105** is input to a filter network **901**. The filter network **901** includes N filters **902, 903, 904**. The transfer functions of the individual filters **902, 903, 904** can be represented as $H_i(f)$, where $i = 1$ to N. The outputs of the N filters **902, 903, 904** are combined at a first summation node **905**. The output of the first summation node **905** is multiplied by the control variable **106**, which varies with channel length. The control variable alpha, α, ranges in

value from 0 to 1 depending on the amount of compensation needed to restore the signal fidelity of the received signal. The output of an all-pass data path **906**, in parallel with the filter network **901**, is then summed with the output of the multiplier **907** at a second summation node **908**. The output of the second summation node **908** provides the equalized signal **102**. The total transfer function of the adaptive equalizing filter **101** shown in Figure 4 is given as:

$$H_{TOTAL}(\alpha, f) = 1 + \alpha \sum_{i=1}^{N} H_i(f).$$

One skilled in the art will readily appreciate that the present invention supports variations of the exemplary the filter network **901** illustrated in Figure 9. More specifically the filter network **901** can be readily adapted according to the needs of various applications. Ideally, for a specified maximum channel length, L, $H_{TOTAL}(f)$ should equal the inverse of the channel loss when $\alpha = 1$. In many applications, an exact match is not feasible and the filter transfer function is designed to approximate the inverse of the channel as closely as possible while ensuring that the composite group delay of the channel and filter remains relatively constant as a function of frequency to reduce jitter in the equalized signal. Hence, the actual architecture of an adaptive Bode equalizer may change significantly from the exemplary architecture shown in Figure 9 in order to better approximate the inverse of a particular channel response. While the example **101** shown in this figure uses a network of parallel filters, serial filters or a combination of serial and parallel filters may be preferable for certain channels. Likewise, the circuit shown in Figure 9 can constitute only one stage of a multi-

stage equalizing filter, where each stage is controlled by a separate control variable. In any case, the individual filter transfer functions, $H_i(f)$, can be optimized for a given channel so that:

$$H_{TOTAL}(\alpha = 1, f) \approx [H_{CHANNEL}(l = L, f)]^{-1}.$$

Finally, the level of adaptation of the embodiment shown in Figure 9 amounts to scaling the output of the filter network **901** by alpha, α, reducing the amount of applied compensation for channel lengths less than L. More complex Bode architectures may use one or more control variables to shift the locations of the poles and zeros in the individual filter transfer functions to better compensate for channel loss at intermediate lengths.

Turning now to Figure 10, this figure illustrates an equalizing circuit **1000** according to an exemplary embodiment of the present invention. Under feedback control, an adaptive equalizer **101** restores signal fidelity to the received signal **105** by compensating for channel loss and dispersion and also alleviates receiver sensitivity to transmit amplitude and signal spectrum.

Circuit **1000** uses the difference in edge energies of the equalized signal **102** and the quantized signal **104** to determine an error signal **1024**, which, in turn, adjusts the control variable **106**. The circuit **1000** uses a combination of filtering and power detection to measure edge energies. For the equalized signal **102** and the quantized signal **104**, high-pass filter **1004** and high-pass filter **1013**, respectively, isolate the appropriate frequency components corresponding to edge

energy, and the signal energy in the frequency range determined by these filters **1004, 1013** is measured with power detectors **1005, 1014**.

Before generating the error signal **1024**, the edge energy measurement **1006** of the equalized signal **102** is scaled by a measure of the low-frequency energy **1018** in the quantized signal **104**. Likewise, the edge energy measurement **1015** of the quantized signal **104** is scaled by a measure of the low-frequency energy **1009** in the equalized signal **102**. The low-frequency energy measurements **1009, 1018** for the equalized and quantized signals **102, 104** are obtained by low-pass filtering the respective signals **102, 104** with low-pass filters **1007, 1016** and feeding the filtered outputs into power detectors **1008, 1017**.

If the power detectors **1005, 1008, 1014, 1017** used for both the low-frequency and edge energy measurements incorporate integrators, the scaling functions are typically performed at speeds that are orders of magnitude less than the data rate. The error signal **1024** is generated by subtracting the edge energy **1006** of the equalized signal **102,** scaled by the low-frequency energy **1018** of the quantized signal **104,** from the edge energy **1015** of the quantized signal **104,** scaled by the low-frequency energy **1009** of the equalized signal **102.**

The scaling function accounts for any discrepancy that may exist between the peak-to-peak amplitude of the equalized signal **102** and that of the quantized signal **104** since any such discrepancy will be manifested in the low-frequency signal energies **1009, 1018.** Thus, the error signal **1024** correlates to the difference in edge energies of the equalized and quantized signals **102, 104** and is not skewed by any low-frequency discrepancies that may exist between the two

signal spectra. As such, the circuit **1000** is insensitive to changes in transmit amplitude, which correlate to changes in the equalized signal amplitude.

A first control signal **1001** is tapped off from the equalized signal **102** and subsequently split into a first parallel control signal **1002** and a second parallel control signal **1003**. The first parallel control signal **1002** is input to a first high-pass filter **1004**, the output of which is, in turn, input to a first power detector **1005**. The cutoff frequency of the first high-pass filter **1004** is typically greater than or equal to half the data rate. If the adaptive equalizer **1000** is intended to operate over a range of data rates, the cutoff frequency of high-pass filter **1004** is typically greater than or equal to half the minimum data rate.

Power detector **1005**, which can include an integrator (not shown in the Figure 10), outputs a signal **1006** that has an amplitude that is proportional to the edge energy of the equalized signal **102**. The bandwidth of the integrator is typically chosen to be several orders of magnitude less than the minimum data rate. The output **1006** of the first power detector **1005** is denoted as S_1. The second parallel control signal **1003** is input to a first low-pass filter **1007**, the output of which is, in turn, input to a second power detector **1008**. The cutoff frequency of the low-pass filter **1007** is typically equal to the cutoff frequency of high-pass filter **1004**. Power detector **1008**, which is similar to power detector **1005**, outputs a signal **1009**, whose amplitude is proportional to the low-frequency energy of the equalized signal **102**. The output **1009** of power detector **1008** is denoted as S_2.

A second control signal **1010** is tapped off from the quantized signal **104** and subsequently split into a third parallel control signal **1011** and a fourth parallel control signal **1012**. The third parallel control signal **1011** is input to high-pass filter **1013**, the output of which is, in turn, input to power detector **1014**. The cutoff frequency of the high-pass filter **1013** can approximate that of the high-pass filter **1004**. Power detector **1014**, which is typically similar to power detector **1005**, outputs a signal **1015** whose amplitude is proportional to the edge energy of the quantized signal **104**. The output **1015** of the power detector **1014** is denoted as S_3.

The fourth parallel control signal **1012** is input to a low-pass filter **1016**, the output of which is, in turn, input to power detector **1017**. The cutoff frequency of the low-pass filter **1016** can approximate that of the low-pass filter **1007**. Power detector **1017**, which is also typically similar to power detector **1005**, outputs a signal **1018** whose amplitude is proportional to the low-frequency energy of the equalized signal **102**. The output **1018** of power detector **1017** is denoted as S_4.

In practice, the power detectors **1008**, **1005**, **1014**, **1017** can be realized as simple squaring blocks with each having an integral low-pass filter (not shown). Such integral filters cause the power detector outputs to vary slowly compared to the data rate of the quantized signal **104**. Typically, the bandwidth of these integrating filters will be several orders of magnitude less than the data rate. The outputs of the power detectors **1008**, **1005**, **1014**, **1017** typically correspond to an

analog estimate of the statistical variances (i.e. the square of the standard deviation) of the respective control signals.

As an alternative to a squaring block, each power detector **1008, 1005, 1014, 1017** can include full-wave rectifiers or half-wave rectifiers (not shown). Using rectifiers, the outputs of the power detectors **1008, 1005, 1014, 1017** do not typically correspond to error variances. Instead, the power detector outputs based on rectifiers represent the approximate 1-norm of the respective control signals, which still correlates well to signal energy in the desired frequency range.

The signal S_1 **1006** and the signal S_4 **1018** are input to a first multiplier **1019**, and the resulting product **1020** is fed to a first input of a summation node **1021**. The signal S_2 **1009** and the signal S_3 **1015** are input to a second multiplier **1022**, and the resulting product **1023** is fed to a second input of the same summation node **1021**. The summation node **1021** subtracts the first input **1020** from the second input **1023** to generate the error signal **1024**.

The error signal **1024** varies slowly compared to the data rate and is proportional to the difference in edge energies of the equalized signal **102** and the quantized signal **104**, scaled by the low-frequency energies of these signals **102, 104**. The error signal can be represented as:

$$Error\ Signal\ =\ S_2S_3-S_1S_4.$$

A control block **1025** converts the error signal **1024** into the control variable **106,** which is fed back to the adaptive equalizer **101**. A simple implementation of the control block **1025** can include a scaling amplifier and an added offset.

In certain applications, band-pass filters may be substituted for the high-pass filters **1013, 1004** and/or the low-pass filters **1007, 1016** that are illustrated in Figure 10. For example, the bandwidth limitations of an equalizing filter, in some cases, can prevent the equalized signal from ever attaining an edge energy equivalent to the quantized signal, and the high-pass filters **1013, 1004** should be replaced with band-pass filters to address this condition. In such a case, the pass bands can span a frequency range over which the spectra of the equalized and quantized signals **102, 104** are equivalent when the outputs of the filters are appropriately scaled by low-frequency energies and the equalizer has been adjusted to its optimal setting.

One skilled in the arts will recognize that an alternative embodiment of the circuit **1000** may include fixed gain blocks following the filters **1004, 1013**. These gain blocks could be used to offset known discrepancies in the scaled signals **1020, 1023**. For example, if the bandwidth limitations of the equalizing filter prevent the equalized signal from ever attaining edge energies comparable to the quantized signal and the bandwidth limitations of the filter are known, the gain blocks can re-scale either or both of the scaled signals **1020, 1023** to account for this discrepancy and enable the equalizing filter to properly equalize the received signal.

Circuit **1000** can function adequately without an AGC element in the data path by providing an automatic gain control function in the control loop via the low-frequency scaling function. That is, the low-frequency scaling function provides automatic gain control that is integral to the control loop **410** and does

not require discreet, dedicated AGC circuit components. Since the scaling function occurs after the control signals are integrated, the de facto automatic gain control of Circuit **1000** further simplifies the control loop architecture since one or more separate high-speed AGC components in the data path are not required.

One skilled in the art will appreciate that the present invention supports applying automatic scaling of the control signals to generate an accurate error signal in numerous applications. For example, a measured parameter related to signal spectrum other than edge energy can be used to adapt the equalizing filter.

As an alternative to the multipliers illustrated in Figure 10, the present invention can include AGC amplifiers outside of the data path. Turning now to Figure 11, this figure illustrates a circuit **1100** with AGC amplifiers **1101, 1102** according to an exemplary embodiment of the present invention. Signal S_1 **1006** is input to the AGC **1101,** while signal S_3 **1015** is input to the AGC **1102.** Signal S_4 **1018** is used to control the gain of AGC **1101,** while signal S_2 **1009** is used to control the gain of the AGC **1102.** The output **1103** of the AGC **1101** is subtracted from the output **1104** of the second AGC **1102** at the summation node **1021.** The output **1024** of the summation node **1021** is an error signal **1024** proportional to the difference in edge energies of the equalized signal **102** and the quantized signal **104,** scaled by the low-frequency energies of these signals **102, 104.**

Similar to the circuit **1000** illustrated in Figure 10, the error signal **1024** of Circuit **1100** can be represented as:

$$Error\ Signal = S_2 S_3 - S_1 S_4.$$

The control loop **410** of Circuit **1100** alleviates the need for automatic gain control in the data path by using automatic gain control at a much lower bandwidth to appropriately scale the control signals used to generate error signal.

In one embodiment of the present invention, band-pass filters are substituted for the high-pass filters **1004** and **1013**. Such an embodiment may provide advantages for some applications in which the limitations of circuit technologies may make high-pass filters infeasible or when the application benefits from control variable adjustments based on a signal parameter other than edge energy. In one embodiment of the present invention, the pass bands of each band-pass filters can be equal to one another and chosen so as to isolate the portion of the signal spectra that best correlates to the desired signal parameter. In one embodiment of the present invention based on band-pass filters, the cutoff frequency of the low-pass filters **1007** and **1016** will remain at approximately half the minimum data rate.

In an alternative embodiment of the present invention, circuit **1100** uses the AGCs **1101, 1102** to scale the AGC outputs **1103, 1104** to account for a known discrepancy in the monitored signal parameters of the equalized and quantized signals **102, 104**. For example, if the bandwidth limitations of the equalizing filter prevent the equalized signal from attaining edge energies comparable to the quantized signal and the bandwidth limitations of the filter are known, the AGCs can scale either or both of the scaled signals **1103, 1104** to

account for this discrepancy and enable the equalizing filter to properly equalize the received signal.

Those skilled in the art will appreciate that, although the embodiments illustrated in Figures 10 and 11 are single-ended, the invention may be implemented in a differential architecture when necessitated by the design requirements of a receiver.

Turning now to Figure 12, this Figure illustrates an exemplary process **1200**, entitled Adaptive Equalization, that corrects distortion in a communication channel. Step **1210** is the first step in the process in which an adaptive equalizing filter **101**, such as a Bode equalizer, accepts a distorted communication signal from a medium **303**, as illustrated in Figure 3. The medium **303** can be lossy and dispersive and can impart noise **304** or other signal impairments on the communication signal as well.

At Step **1220**, the adaptive equalizing filter **101** compensates for distortion of a communication signal due to frequency-dependent loss and ISI induced by a communication channel, such as a lossy transmission cable. When the equalizing filter settings are optimized, the corrected signal exhibits a signal fidelity similar to the signal that was launched into the opposite end of the communication channel, before undergoing transmission distortion.

The adaptive equalizing filter **101** can be a Bode equalizer or other device that corrects signal distortion. The adaptive equalizing filter **101** is adjustable so that it can be adapted or controlled to provide equalization to a broad range of signals and data rates under a broad range of operating conditions. This filter **101**

provides a level of equalization that is adjustable under control of a control loop **410**. The filter **101** can also include one or more filtering parameters that can be adjusted to vary the level or degree of equalization that is applied to various frequency components of the communication signal.

At Step **1225**, the equalized signal **102** that is output by the adaptive equalizing filter **101** is coupled to a comparator **103** or other quantizing device. A quantizing device is a device that provides two or more discrete outputs based on the intensity of an input signal. That is, a quantizing device outputs two or more signal levels based on comparing an input signal to another signal.

At Step **1230**, the comparator **103**, or other quantizing device, compares the equalized signal **102** to a reference and amplifies the difference. In one embodiment of the present invention, the comparator **103** provides two or more discrete signal levels based on the results of the comparison. The comparator **103** outputs a quantized signal based on its comparison. In the case of a digital transmission system, the quantized comparator output can consist of a two-level digitized signal.

At Step **1235**, a control circuit **410** observes the equalized signal **102** and the quantized signal **104**. That is, the control circuit **410** taps both the communication signal leading into the comparator **103** and the communication signal leading out of the comparator **103**.

At Step **1240**, the control circuit **410** monitors a signal parameter in each of the equalized signal **102** and the quantized signal **104**. In one embodiment of the present invention, this monitored parameter is edge energy or high-frequency

signal strength and the control circuit **410** can include filters **1004, 1013** to extract high-frequency signal components. Monitoring or detecting edge energy or high-frequency signal strength, as described herein, is not limited to quantifying edge energy or high-frequency signal strength on a scale with units such as decibels or milliwatts. Rather, monitoring or detecting edge energy or high-frequency signal strength can include establishing a voltage or current signal that is directly or indirectly correlated with edge energy or high-frequency signal strength. The present invention can use such a current or voltage signal without assigning a specific voltage or current measurement to the signal. That is, the present invention can control an adaptive equalizing filter **101** based on monitoring signal levels without measuring such signals on a scale.

At Step **1250**, the control circuit **410** monitors the low-frequency power or energy in each of the equalized communication signal **102** and the quantized communication signal **104**. In one embodiment of the present invention, the control circuit **410** conducts this monitoring by filtering the sampled equalized signal and the sampled quantized signal using low-pass filters **1007, 1016** and feeding the filter outputs to power detectors. The filtered equalized signal and the filtered quantized signals are coupled to respective detectors, such as power detectors **1008, 1017**.

At Step **1260**, the control circuit **410** scales the monitored parameter of the quantized communication signal **104** according to the low-frequency energy in the equalized signal **102**. In a similar manner, the control circuit **410** scales this monitored parameter of the equalized communication signal **102** according to the

low-frequency energy in the quantized signal **104**. This scaling effectively compensates for low-frequency power variations in the transmitted communication signal.

At Step **1270**, the control circuit **410** compares the scaled parameters to one another. That is, the control circuit **410** compares the monitored parameter in the equalized signal **102** to the monitored parameter in the quantized signal **104**, taking into account, or compensating for, low-frequency power drift, variation, or fluctuation.

At Step **1280**, the control circuit **410** adjusts the degree or level of equalization applied by the adaptive equalizing filter **101** based on the comparison. The control circuit **410** adjusts one or more parameters of the adaptive equalizing filter **101** in a manner that minimizes or otherwise reduces the difference between the two scaled parameters. For example, when the control circuit **410** sets the adaptive equalizer filter **101** to provide optimal equalization to the communication signal, the difference between the scaled parameter of the equalized signal **102** and the scaled parameter of the quantized signal **104** can reach a minimum value. Process **1200** iterates Step **1220** through Step **1280** to provide continual adaptation. This action helps the receiver to correct for a broad range of operating conditions, signal variations, and data rates.

Although the present invention can comprise a circuit that controls an adaptive Bode equalizer for a digital communication channel, those skilled in the art will appreciate that the present invention is not limited to this application and that the embodiments described herein are illustrative and not restrictive.

Furthermore, it should be understood that various other alternatives to the embodiments of the invention described here may be employed in practicing the invention. The scope of the invention is intended to be limited only by the claims below.